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PROGRAM ELEMENT: #1, Pacific Northwest Region

PROJECT TITLE: EARTHQUAKE HAZARD OF THE UPPER COOK INLET FOLD BELT, GREATER ANCHORAGE AREA, ALASKA

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TECHNICAL ABSTRACT

Plicocene to Quaternary age structures in upper Cook Inlet Basin of Southcentral Alaska are fault propagation folds and strike- to oblique-reverse slip faults that may pose significant fault displacement and groundshaking hazard to the Greater Anchorage area. Folds in upper Cook Inlet are cored by stepply dipping faults, most of which do not reach the surface. These faults core folds that have developed mostly during Pliocene time, but there is some evidence that folding has continued into the Quaternary based on patterns of stream drainages that cross folds, anomalous patterns of uplift along the sea coast, and folded reflectors on seismic reflection profiles collected by the petroleum industry. The evidence for Quaternary, and in particular, Holocene age fault-propagation folding is for the most part ambiguous because of extensive modification of the landscape by glaciers, and the limited resolution of industry reflection data at shallow depths. Holocene surface faulting

has occurred the Castale Mountain fault which is located at the northeastern end of the Cook Inlet deformation belt.

Structural analysis of outcrops, bore hole and seismic reflection data indicates that most faults are oblique-slip features that dip steeply to the either the northwest or southeast in the subsurface. The lateral dimensions of the faults were estimated by analysis of structure contour maps. Fault lengths are sufficient to generate M 6 or greater earthquakes if rupturing does occur.

The research provides new motivation for careful analysis and dating of Quaternary sedimentary deposits and geomorphic features in the upper Cook Inlet basin to directly address the problem of Pleistocene and Holocene tectonic activity. The present study provides a structural and tectonic framework, but did not resolve the issue of present day deformation rates, which is required before the seismic hazard can be quantified.

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NON-TECHNICAL ABSTRACT

Folds and faults in upper Cook Inlet Basin of southcentral Alaska were studied to determine their potential as sources of damaging earthquakes. The work was performed by mapping geological features and deposits in the field, and studying subsurface well and seismic data, which reveals the presence of buried structures. We concluded that a number of folds are cored by buried, or blind, faults which may be capable of generating large earthquakes of magnitude 6 or greater. The Castle Mountain fault is know to be active because it has offset deposits less than 10,000 years old in the Susitna lowlands at the northeast end of Cook Inlet Basin. Conclusions concerning the activity of other structures in the basin requires further work to date the youngest deposits offset by faults or affected by folding.

INTRODUCTION

Do fault-propagation folds in upper Cook Inlet pose significant earthquake hazard to the greater Anchorage area, which is the demographic and economic center of Alaska? Evidence for the structural style and age of deformation of upper Cook Inlet folds was studied starting May 1, 1996 to address this question. Two papers were submitted for publication in the Geological Society of America Bulletin as the results of this project:
1) Plicocene or Quaternary Deformation in Cook Inlet Forearc Basin, Alaska by P.H Hauessler, R.L. Bruhn, and T.L. Pratt.
2) Tectonics and fluid pressure distribution in a deformed forearc basin, Cook Inlet, Alaska by R.L. Bruhn, W.T. Parry and M.P. Bunds.
The second paper is now being revised for final acceptance and publication, the first paper remains under review as of Sept., 1998.

Preliminary results were reported previously as oral presentations at the American Geophysical Union Fall Meeting in San Francisco, CA (Bruhn et al., 1996; Haeussler et al., 1996).

Subsurface information about the structural style, earthquake potential and age of fault-propagation folding was evaluated. Data included exploration seismic reflection profiles donated to the project by ARCO, Alaska, Inc., several high-resolution seismic reflection lines recorded during an oil platform engineering survey, structural contour maps of oil and gas fields (Alaska Oil and Gas Commission, 1995), and oil and gas well logs and completion reports on file with the Alaska Oil and Gas Conservation Commission. Field investigations included inspection of geomorphic features that may indicate Quaternary folding in upper Cook Inlet. Airphoto and topographic map interpretation was supplemented by the collection of radiocarbon samples to date Quaternary deposits, and reconnaissance of selected outcrops to determine the style of faulting and folding.

The conclusion to date is that the two belts of fault-propagation folds located along the margins of upper Cook Inlet are likely sources of Mw 5.8 to 7+ earthquakes generated by rupturing on buried faults. These structures pose significant hazard because of proximity to Anchorage and surrounding cities and towns, and an infrastructure of transportation routes, electrical transmission lines, and oil and gas production and refining facilities. The buried faults pose separate hazards in addition to the hazard posed by subduction zone earthquakes, and rupturing of the Castle Mountain fault.

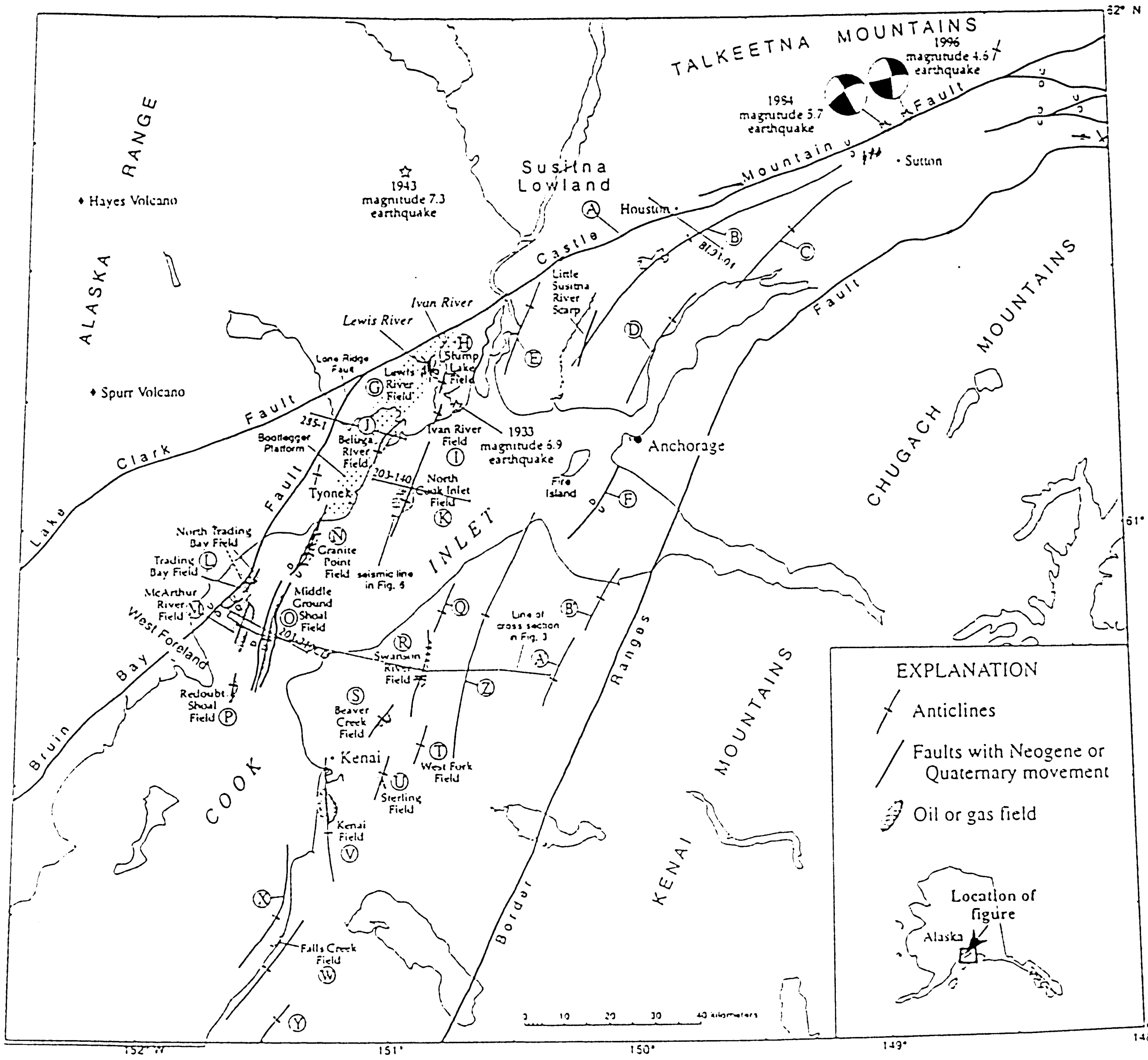

Figure 1: Tectonic map of the Cook Inlet region with major folds and faults. Figure reproduced from Haeussler et al. (under review).

The research is a collaborative effort between R.L. Bruhn of the University of Utah, and P.H. Hauessler and T. Pratt of the US Geological Survey. This report is written by Bruhn to summarize work as of February, 1997, as part his commitment to the USGS extramural research program. A manuscript on earthquake hazards in upper Cook Inlet is being prepared for submission to the Geological Society of America Bulletin with authorship by Haeussler, Bruhn and Pratt. A summary of the work was presented at the 1996 Fall meeting of the American Geophysical Union by Haeussler and Bruhn (1996). Additional structural data together with details of the fluid pressure regime in Cook Inlet basin were discussed by Bruhn et al. (1996) at the same meeting. Several paragraphs in this report are taken from the draft manuscript of Hauessler, Bruhn and Pratt (Hauessler et al., in preparation). Work continues to complete geologic cross sections and interpretation of geomorphic anomalies.

TECTONIC SETTING OF UPPER COOK INLET

Cook Inlet basin is a northeast-trending forearc basin located between the Chugach and Kenai Mountains to the southeast, and the Alaska Range and Aleutian volcanic arc to the northwest (Fig. 1). The Aleutian volcanic arc dies out to the northwest of the basin. The depth to the subducting Pacific plate is approximately 50 km beneath the center of the basin, and is much deeper on the northwest side of the basin (Page and others, 1991). Major fault zones lie close to the margins of the basin on three of its sides: the Castle Mountain fault on the north, the Bruin Bay fault on the northwest, and the Border Ranges fault along the southeast side (Fig. 1). Most rocks in the Chugach and Kenai Mountains are part of a vast accretionary complex, and rocks of much of the Alaska Range formed part of a microcontinent that accreted to North America during Cretaceous time (Plafker and others, 1994). Therefore, the basin is an overlap assemblage that straddles the boundary between the accretionary complex and its backstop, but the mapped contact between these crustal fragments lies near the southeastern edge of the basin. Cook Inlet basin has a long depositional history since early Mesozoic time (Kirschner and Lyon, 1973). Recent deposition was dominated by detritus derived from erosion of the Alaska range (Kirschner and Lyon, 1973). As a result, the Pliocene-and-younger-age Sterling Formation is more than 1,600 m thick in parts of the basin (Kirschner and Lyon, 1973; Hartman et al., 1972). Other formations relevant to our discussion include the include the latest Oligocene through middle Miocene Tyonek Formation, the late Miocene Beluga Formation, (the previously mentioned Pliocene Sterling Formation), and unnamed Quaternary sediments.

Middle Ground Shoal

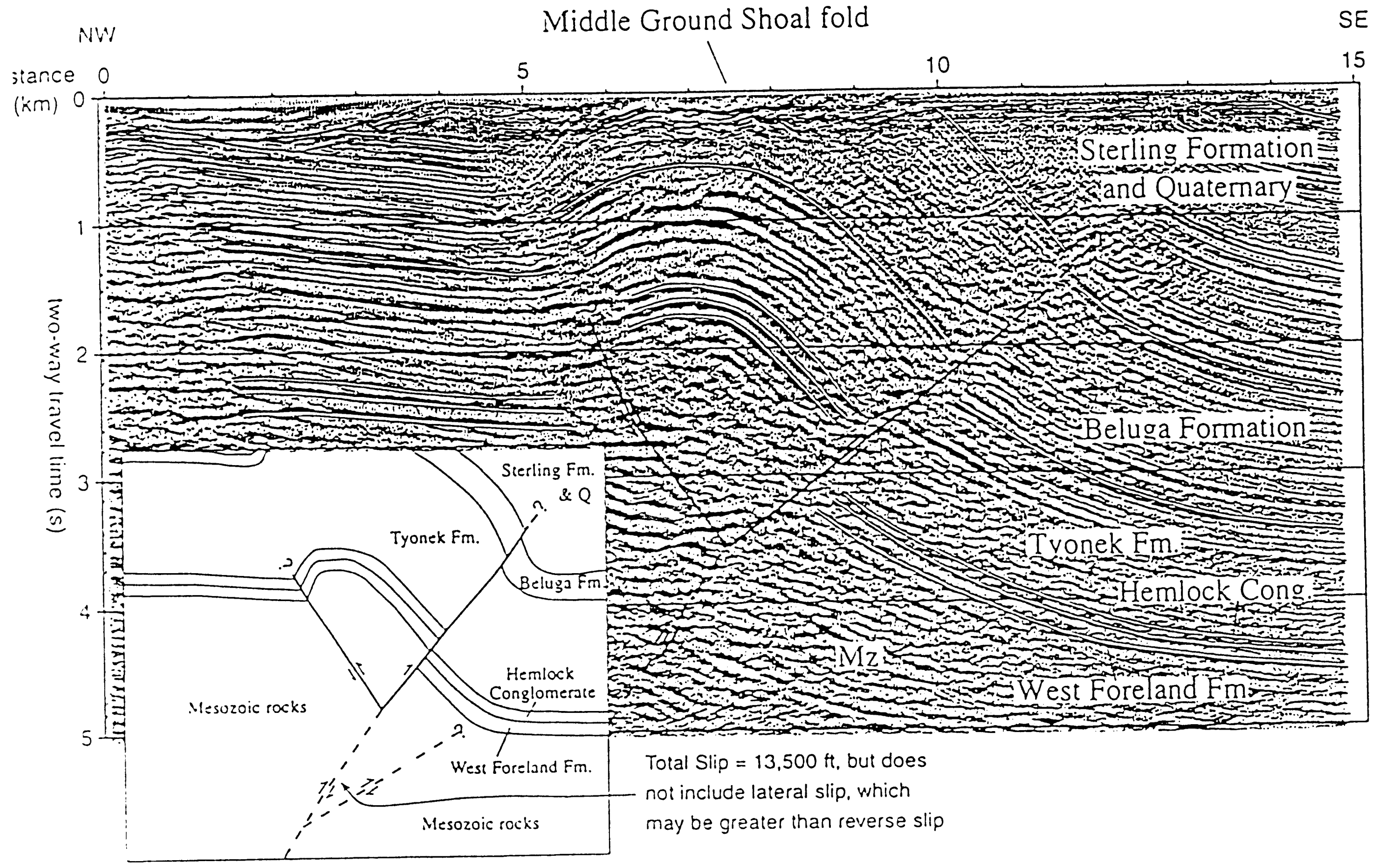

Figure 2: Seismic reflection profile and cross section of Middle Ground Shoal anticline. See Figure 1 for location of Middle Ground Shoal Field. Figure is reproduced from manuscript by Haeussler et al. (under review)

Upper Cook Inlet region is the area northeast of West Foreland, a prominent peninsula that extends into Cook Inlet (Fig. 1). This region is notable because it contains the greater Anchorage area, which is the population and infrastructure center of Alaska. Upper Cook Inlet basin is also an important oil and gas province with production platforms, underwater and surface pipelines, and refineries.

FAULT PROPAGATION FOLDS

A cross section of the Middle Ground Shoal fold (Figs. 1 & 2) is used to illustrate the structural style of fault-propagation folding in upper Cook Inlet. Middle Ground Shoal oil field is located in one of the more spectacular and better studied folds (Fig. 2). This is an open, asymmetric, and northwestward-vergent fault-propagation fold. The northwestern limb is subvertical as delineated by drilling, and the eastern limb dips approximately 45° (Fig.2; Boss et al., 1976). Cross sections drawn by several authors (Boss et al., 1976; Kirschner and Lyon, 1973; Magoon, 1994) all show reverse faults in the fold core, but the geometry and depth extent of these faults are controversial. Kirschner and Lyon (1973) sketch a single, SE-dipping reverse fault cutting into Jurassic rocks. Boss et al. (1976) show a NW-dipping master reverse fault that roots along the Tertiary - Mesozoic contact, with a secondary, SE-dipping back-thrust. Magoon (1994) sketches a SE-dipping master reverse fault that cuts into the Jurassic section, and shows the NW-dipping fault as the secondary back-thrust. These cross sections all show a regional down-to-the-southeast basement step along the Middle Ground Shoal trend, but do not provide an explanation for its origin. We propose a cross section similar in the upper part to that of Boss et al. (1976), but continue the NW-dipping master reverse fault deep into the Mesozoic basement (Fig. 5), a structural configuration that is consistent both with the geometry of the shallow Middle Ground Shoal fold and the regional basement step. Thus, this deeper main thrust is a blind fault, and the shallower back thrust coring the Middle Ground Shoal anticline is a blind backthrust, both with an unconstrained amount of oblique motion.

GEOMORPHIC EVIDENCE FOR QUATERNARY DEFORMATION

Several geomorphic and surface geology features were visited in the field during the summer of 1,996 following review of previously published literature, a study of aerial photography and a regional air and ground reconnaissance of sea cut bluffs surrounding Cook Inlet. Several features are notable as possible evidence for Quaternary fault-propagation folding, but the complex geodynamics of the Cook Inlet region and lack of high-resolution topographic mapping makes it difficult to differentiate between various processes that may create uplifted features and peculiar stream drainage patterns. Quaternary uplift is indicated by wave-cut bluffs, by emergent beach berms at headlands and in the interior of low-relief platforms, by abandoned stream deposits flanking incised stream valleys, and by entrenched stream channels (Kelly, 1961; Tysdal, 1976; Schmoll and Yehle, 1984). Separating uplift caused by isostatic rebound following deglaciation from that caused by fault-propagation folding remains a fundamental problem. Preliminary interpretations of several geomorphic features that may be related to fault-propagation folding are discussed below.

A diamicton exposed in bluffs at Granite Point on the northwest side of Cook Inlet dips between 5° and 7° northwest below horizontal peat deposits, indicating Quaternary folding of the Granite Point anticline (Fig. 1). Alternative hypotheses for the origin and age of the diamicton are discussed by Schmoll et al. (1984). We conclude, following both review their work and our own field study, that the diamicton is most likely a Pleistocene-age till with thin, discontinuous fluvial layers and lenses, and allochthonous coal derived from the late Miocene Beluga Formation. A minimum age for folding is provided by radiocarbon dates from overlying, horizontal peat beds. The basal peat has a calibrated age of 14,304 yr. B.P. (Hauessler and Bruhn, 1996; unpublished data).

The folded till at Granite Point is exposed in bluffs just south of abandoned stream deposits that grade to an old shoreline or 'platform' at an elevation of approximately 50 m according to Schmoll et al., 1984. This uplifted surface may correlate with the Bootlegger Cove Platform to the northeast according to Schmoll et al. (1984). The Bootlegger Cove Platform is a low-relief surface with abandoned marine shoreline deposits that extends for tens of kilometers along the northwest side of upper Cook Inlet (Fig. 1; Schmoll et al.,1984; Schmoll and Yehle, 1992).The platform is partly developed on Pleistocene glacioestuarine sediments of the Bootlegger Cove Formation (14,350 ± 200 radiocarbon yr. B.P.; Updike et al., 1982) at an elevation between approximately 20 and 50 m above sea level. Abandoned beach deposits on the platform surface are dated as about 8k - 9k yr. B.P. (Schmoll and Yehle, 1992; Stuiver and Reimer, 1993). The platform overlies several folds between Granite Point and the Susitna River. The escarpment along the southeastern edge of the platform could originate by a combination of tectonic uplift during folding, followed by erosion due to stream and wave action. Anecdotal reports following an Ms 6.9 earthquake in 1933 suggest intense shaking and ground failure in this region (Anchorage Daily Times, April 27 through March, 1933).

Kelly (1961) proposed that active folding in upper Cook Inlet creates geomorphic anomalies in Quaternary and younger deposits. He speculated, for example, that the Ivan River is deflected around a growing anticline located adjacent to the northeastern part of the Bootlegger Cove platform (Fig. 1). Kelly's speculation is supported by the discovery of the Stump Lake gas field in 1978, which is located on an anticline that is covered by emergent Holocene fluvial and tidal deposits. New structural data gathered since the 1960's shows that the Ivan River follows a circuitous course to Cook Inlet that apparently avoids the subsurface structural 'highs' of the Lewis River, Ivan River, and Stump Lake anticlines (Fig. 1; Alaska Oil and Gas Conservation Commission, 1995), which further supports the notion that the folds are active. The course of the Lewis River may also be partly controlled by buried structures; the river crosses the Boot Leggier Cove Platform near the southern end of the complexly faulted Lewis River anticline, then turns almost parallel to the axis of a buried syncline located adjacent to the western flank of the Ivan River gas field before discharging into Cook Inlet. The course of the Beluga River may also be partly controlled by the rising flanks and plunging hinge of the Beluga fault-propagation anticline, which is located beneath the Bootlegger Cove Platform along the western side of Cook Inlet (Fig. 1).

UPPER COOK INLET FOLDS AS POTENTIAL EARTHQUAKE SOURCES

Preliminary estimates of potential earthquake sources and magnitudes in upper Cook Inlet are discussed by Haeussler and Bruhn (1996) and a detailed list is given in tabular form the manuscript that is under preparation (Haeussler et al., in preparation). We have identified 18 fault-propagation folds that may act as independent, or in some cases linked, earthquake sources (Haeussler and Bruhn, 1996; Hauessler et al., in preparation). Lengths of individual folds range from 6 to 27 km, corresponding to buried faults capable of generating earthquakes with moment magnitudes ranging from approximately 5.5 to 6.5. Fault rupturing along the combined 44-km length of the Middle Ground Shoal–Granite Point structure could generate an earthquake of approximately Mw 6.8, and the magnitude potential of the combined Redoubt Shoal–McArthur River structure is similar. Holocene surface scarps along the Castle Mountain fault zone are approximately 60-km long, a rupture length consistent with an Mw 7.1 paleoearthquake. A table of fault-propagation fold sources together with estimated lengths, magnitude potential, and information on data sources is presented in the attached manuscript by Hauessler et al. (under review).

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FIGURE CAPTIONS

Figure 1: Tectonic map of the Cook Inlet region with major folds and faults. Figure reproduced from Haeussler et al. (under review).

Figure 2: Seismic reflection profile and cross section of Middle Ground Shoal anticline. See Figure 1 for location of Middle Ground Shoal Field. Figure is reproduced from manuscript by Haeussler et al. (under review)